Mini review

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Phytochemical profile and preservation efficacy of Moringa oleifera: a regulatory and mechanistic mini-review

Abstract

Moringa oleifera offers promising natural food preservation properties through its diverse phytochemical profile dominated by glucosinolates, isothiocyanates, flavonoids, and phenolic acids. This mini-review synthesizes recent evidence on *M. oleifera's* multifunctional antimicrobial and antioxidant mechanisms, particularly relevant for food preservation applications. The European Union's Novel Foods Regulation (EU 2015/2283) and the US FDA's GRAS evaluation framework require standardized extraction protocols, safety data, and quality control specifications for commercial adoption. Documented applications span meat products (achieving 49-100% pathogen inhibition), edible fruit coatings (extending shelf life 21-28 days), and oil stabilization, with sensory acceptability maintained at optimal concentrations (0.5-1%). However, regulatory gaps remain regarding FERA (Food Emulsifiers, Regulators, and Additives) status, requiring comprehensive toxicological studies and standardized quality benchmarks. Future research directions include optimization of synergistic combinations with complementary antimicrobials, microencapsulation for sensory masking, and validation across diverse food processing conditions. This mini review underscores *M. oleifera's* potential as a scientifically-validated natural preservative with significant commercial promise for clean-label food systems.

Keywords: *Moringa oleifera*, food preservation, glucosinolates, isothiocyanates, antimicrobial, antioxidant, phytochemistry, edible coatings, FERA, natural preservatives

Volume 10 Issue 4 - 2025

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Received: November 11, 2025 | **Published:** December 10, 2025

Introduction

Moringa oleifera Lam. has gained attention as a promising natural alternative to synthetic food preservatives due to its well-documented antimicrobial and antioxidant activities, which contribute to extended shelf life while maintaining product safety and quality.[1] This mini-review synthesizes recent evidence supporting the potential of moringa-derived compounds as Food Emulsifiers, Regulators, and Additives (FERA), with emphasis on its phytochemical profile, preservation mechanisms, and emerging regulatory considerations for commercial use. Although numerous studies describe individual bioactivities of moringa extracts, there remains limited consolidated evaluation of how these chemical constituents interact to deliver multifunctional preservation effects. This review addresses that gap by integrating phytochemical, mechanistic, and regulatory insights into a unified framework.

The antimicrobial and antioxidant properties of *M. oleifera* are increasingly recognized within food science and safety research.[2,3] As industries seek clean-label and naturally derived preservatives, moringa offers a compelling alternative to synthetic agents such as sodium benzoate, BHT, and nitrate-based compounds, which are associated with hypersensitivity reactions and other potential health concerns.[3,4] Figure 1 outlines the key bioactive constituents and their major preservation pathways, highlighting moringa's multifunctional advantages compared with conventional additives (Figure 1).

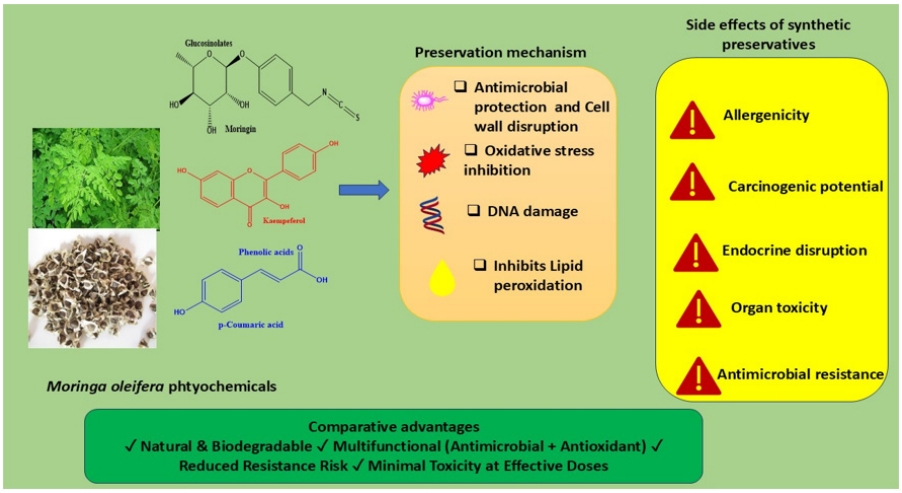

Figure 1 Summary of the key phytochemicals and principal preservation mechanisms of M. oleifera, illustrating its multifunctional advantages over conventional synthetic additives.

Phytochemistry: The chemical foundation of preservation

The food preservation potential of *Moringa oleifera* arises from its diverse phytochemical composition, dominated by sulfur-containing glucosinolates, isothiocyanates, flavonoids, and phenolic acids. Together, these compounds exhibit strong antimicrobial and antioxidant activities that support shelf-life extension in a variety of food matrices. Understanding the chemistry and functional behaviour of these constituents is essential for optimizing moringa-based preservation systems (Table 1).

Table 1 Antimicrobial and antioxidant efficacy of moringa oleifera extracts in food preservation applications.

Food product	Extract type	Concentration	Storage duration & conditions	Target pathogen / biomarker	Key preservation outcome	Efficacy vs. Control	Sensory acceptability	Reference
Chicken meat	Methanolic extract	0.25%	4 days at 4 °C / 25 °C	*E. coli*	0 CFU/g at end of storage	100% inhibition	Good	Dubeni et al.,[21]
Chicken meat	Methanolic extract	1.0%	4 days at 4 °C	*Salmonella* spp.	Complete inhibition	100% prevention	Good–Excellent	Dubeni et al.,[21]
Ground beef	Leaf powder	600 mg/kg	Entire storage period	DPPH activity	Higher antioxidant scavenging	Significant improvement	Good	Hingrajiya et al.
Pork patties	Leaf extract	600 mg/kg	30 days at 4 °C	TBARS	<2.0 mg MDA/kg	Comparable to BHT	Acceptable	Muthukumar et al.[16]
Rabbit nuggets	Leaf powder	1.0%	20 days (chilled)	Aerobic bacteria	49% microbial load reduction	49% improvement	High (100% acceptability)	Munir et al.[17]
Avocados	Edible coating (CMC + MLE)	2% MLE	Post-harvest	PPO activity	50% mass-loss reduction	Significant suppression	Maintained	Ngubane et al.[22]
Fresh tomatoes	Edible coating (fiber + MLE)	Optimal ratio	Ambient (21–28 days)	Spoilage markers	Shelf-life +21–28 days	33% extension	76.01 vs 68.04 control	Umeohia et al.

Glucosinolates and isothiocyanates

M. oleifera contains distinctive glucosinolates, with 4-α-L-rhamnopyranosyloxybenzyl glucosinolates commonly known as glucomoringin (GMG) or 4-RBGS representing the predominant glucosinolate in leaves and seeds (Fahey et la., 2018).[5] This compound possesses a unique structural feature: an additional rhamnose sugar moiety attached to the benzyl ring, distinguishing it from glucosinolates found in other Brassicales plants.[5,6] Upon tissue disruption (cutting, grinding, or mastication), the enzyme myrosinase catalyzes glucomoringin hydrolysis, producing 4- α-L- rhamnosyloxybenzyl isothiocyanates commonly termed moringin.[6] The myrosinase enzyme, α-L- -glucosidase family member and uniquely capable of using ascorbic acid as a cofactor, catalyzes this conversion with remarkable efficiency.[7] This enzymatic transformation generates unstable aglycones that spontaneously rearrange into isothiocyanates or thiocyanates depending on reaction pH and temperature.[8]

The rhamnose substitution in moringa isothiocyanates confers enhanced stability compared to conventional isothiocyanates (e.g., those in cruciferous vegetables), making them particularly suitable for food preservation applications involving thermal processing or extended storage.[5] Recent studies document that moringin exhibits minimum inhibitory concentrations (MIC) of approximately 400 Î¼M against the major foodborne pathogen *Listeria monocytogenes*, with significant antimicrobial activity against *Escherichia coli, Staphylococcus aureus,* and *Salmonella* species.[9] This stability imparted by rhamnosylation enhances bioavailability and prolongs antimicrobial activity during food storage, addressing a critical limitation of many plant-derived preservatives. Additionally, moringin's phase 2 enzyme induction potentials which may exceed that of well-characterized isothiocyanates such as sulforaphanes indicates indirect antioxidant activity through Keap1-Nrf2-ARE-mediated cytoprotective enzyme upregulation.[6] This mechanism provides complementary protection against oxidative damage in stored foods.

Flavonoids

Leaves of M. oleifera contain remarkably high concentrations of flavonoids, identified through advanced phytochemical analysis including high-performance liquid chromatography (HPLC).[10] These flavonoids exhibit characteristic chemical structures with multiple hydroxyl groups positioned strategically on their flavone skeleton, enabling them to function as potent electron donors for free radical neutralization.[3] Among these compounds, hydroxyl groups on the B-ring of quercetin are particularly important for antioxidant activity, providing efficient hydrogen atom donation to reactive oxygen species (ROS) and forming stable quinone products.[1] Moringa flavonoids interrupt lipid peroxidation chain reactions in food systems and chelate pro-oxidant metal ions (copper and iron), thereby maintaining membrane integrity in meat, dairy, and oil matrices.[1,3]

This dual mechanism directly explains the effectiveness of moringa extracts in extending shelf life of oxidation-prone products. Salinity stress studies have demonstrated that M. oleifera cultivated under environmental stress yields increased antioxidant capacity, with DPPH, ABTS, and FRAP assays showing 11-388% enhancement depending on cultivation conditions.[11] This suggests optimization opportunities for producing higher-potency extract batches, opening new avenues for consistent preservation performance. Phytochemical comparative studies establish that *M. oleifera* leaves contain substantially higher flavonoid concentrations (documented in literature at 2.5-4.8% dry weight) than common vegetables, making it one of the richest natural antioxidant sources.[12]

Citation: Sharma AC, Singh S, Chaurasia PK, et al. Phytochemical profile and preservation efficacy of Moringa oleifera: a regulatory and mechanistic mini-review. *MOJ Biol Med.* 2025;10(4):172–177. DOI: 10.15406/mojbm.2025.10.00259

Phenolic acids

M. oleifera leaves also contain phenolic acids such as gallic, caffeic, and ellagic acids, which contribute additional antioxidant and metal-chelating properties.[3] Other identified constituents include tannins, saponins, glycosides, alkaloids, and volatile oils, all of which participate in the multifaceted preservation response of moringa extracts. Phenolic acids act synergistically with flavonoids and moringa-derived isothiocyanates, producing stronger antimicrobial and antioxidant effects than individual compounds alone. Reported synergy factors range from 1.3 to 2.1, supporting the superior preservation efficacy of whole moringa extracts.[2,3]

Antimicrobial mechanisms: Multi-target bacterial inhibition

The antimicrobial effectiveness of the extracts from *M. oleifera* originates in the simultaneous disruption of several bacterial cellular processes, hence developing a multitarget inhibition strategy that minimizes the emergence of antimicrobial resistance-a cardinal advantage over single-mechanism synthetic preservatives.

Cell wall and membrane disruption

Recent mechanistic studies employing scanning electron microscopy (SEM) and transmission electron microscopy (TEM) demonstrate that moringin and other bioactive compounds cause severe structural damage to bacterial cell envelopes.[5] Moringa extracts induce visible disruption of peptidoglycan layers, cell morphology irregularities, cytoplasmic content leakage, and membrane rupture in both Gram-positive and Gram-negative bacteria. Transcriptomic analysis of *L. monocytogenes* treated with moringin revealed substantial downregulation of peptidoglycan biosynthesis genes (MurA and MurC) and cell wall integrity genes, confirming direct targeting of bacterial structural components. The amphipathic nature of isothiocyanates and flavonoids enables their insertion into the lipid bilayer, forming pores that disrupt the membrane potential essential for bacterial viability.[13] This multi-structural targeting prevents efficient adaptation or resistance development, extending antimicrobial efficacy throughout food storage periods.

Induction of oxidative stress in cytoplasm

Moringa compounds initiate intense oxidative stress in bacterial cytoplasm through enhanced ROS production, lipid peroxidation, and exhaustion of intracellular antioxidant defenses.[9] reported that intracellular malondialdehyde (MDA) a biomarker of lipid peroxidation increased significantly in treated L. monocytogenes following moringin treatment compared to controls, reflecting severe membrane damage through oxidative attack.[5] Simultaneously, ROS activity increased to cytotoxic levels, overwhelming bacterial stress response systems.

The oxidative damage mechanism extends beyond membrane lipids to include protein oxidation and enzyme inactivation: moringa phenolic compounds oxidize critical cysteine and methionine residues in bacterial proteins, causing conformational changes with loss of enzymatic function [4]. Oxidative stress mechanisms provide indirect antimicrobial activity that complements direct cellular targeting, reducing the likelihood of resistance development (Figure 2).[3,5]

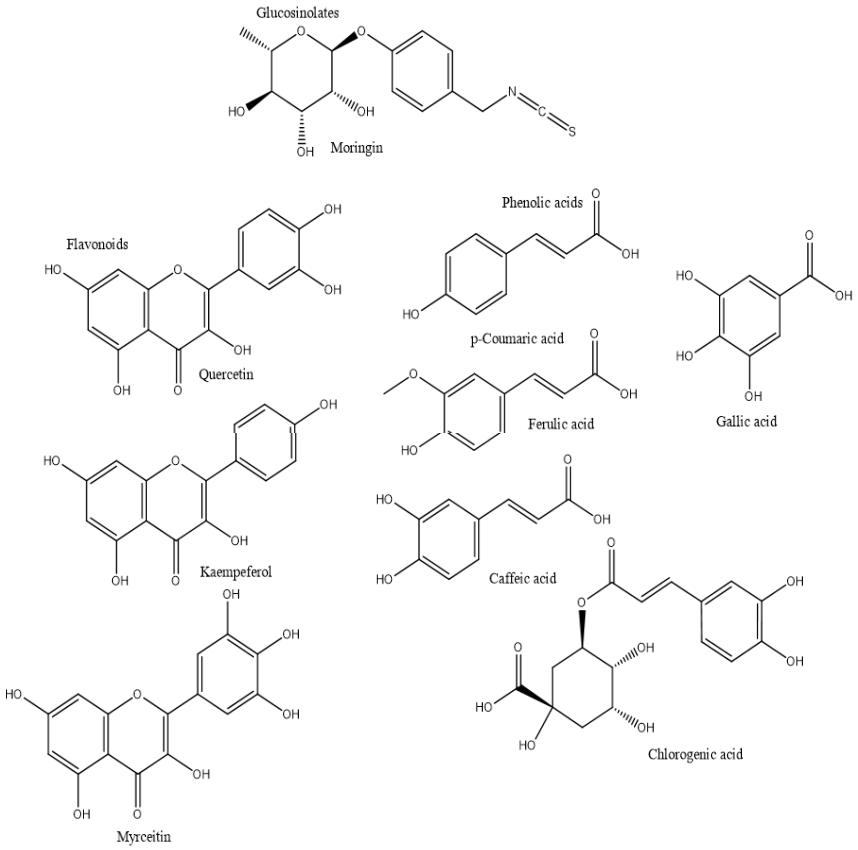

Figure 2 Major components of *M.oleifera* are highlighted for their roles in inhibiting microbial growth, scavenging free radicals, stabilizing cell membranes, and contributing to the overall preservative and therapeutic potential of *M. oleifera*.

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Quorum sensing inhibition and biofilm suppression

Bacterial quorum sensing cell-to-cell communication system coordinating virulence expression, antibiotic resistance, and biofilm formations represents a critical control point for reducing food contamination risk. Moringa phytochemicals inhibit quorum sensing in Gram-negative bacteria through competitive binding to autoinducer receptors of signalling molecules such as acylhomoserine lactones (AHLs), preventing coordinated bacterial behaviour.[14,15] This inhibition prevents mature biofilm development, significantly reducing virulence and persistence in food environments. Biofilm suppression represents an additional preservation mechanism beyond direct bactericidal effects, extending antimicrobial activity to established microbial communities.[14]

DNA interaction and replication inhibition

Molecular docking studies and biochemical assays demonstrate that moringin can intercalate between DNA base pairs, forming stable complexes through hydrogen bonding and hydrophobic interactions. This DNA binding restricts access of replication machinery, effectively inhibiting bacterial proliferation even when cell membrane integrity is only partially compromised. The simultaneous targeting of cellular structure, metabolism, and genetic replication creates a broad antimicrobial spectrum particularly valuable in diverse food preservation contexts.[9]

Mechanistic pathways: antioxidant role in food preservation

The potent antioxidant properties of *Moringa oleifera* not only complement its antimicrobial activity but also mitigate lipid oxidation, a major non-microbial factor affecting food quality, particularly in meat and high-fat products.

Lipid peroxidation inhibition and TBARS reduction

Supplementation with moringa leaf powder in meat patties significantly improved antioxidant potential. DPPH radical scavenging activity was consistently higher in treated samples compared to controls, while TBARS values were maintained below 2.0 mg malonaldehyde/kg, a level associated with consumer health concerns. In fresh ground beef, moringa fortification resulted in lower pH, reduced oxidative changes, and enhanced overall quality compared to untreated samples. In pork patties, 600 mg/kg moringa leaf extract effectively reduced lipid oxidation, performing marginally less than BHT 200 mg/kg for both raw and cooked products. Color stability improved, with reduced metmyoglobin formation and minimal yellow discoloration during storage.[16] By preventing lipid peroxidation, moringa ensures extended shelf life and maintains meat quality during storage.

Development of functional meat products

In rabbit meat nuggets, incorporation of 1% moringa leaf powder reduced microbial load by approximately 49% over 20 days (from 62.17 to 31.88 CFU × 10^3/g), while sensory evaluation indicated high consumer acceptability.[17] Moringa not only enhances preservation but also enables development of functional meat products with acceptable organoleptic properties, demonstrating practical feasibility for commercial applications.[16]

Free radical scavenging capacity

Moringa oleifera extracts demonstrate strong performance across multiple antioxidant assays. Methanolic extracts exhibited 53.3–71.1% DPPH radical scavenging, while both ethanolic and methanolic extracts displayed ABTS activity of 3.83–3.86 g ascorbic acid equivalents/100 g dry matter.[3,18] Strong positive correlations ($r \geq 0.8$, $p < 0.05$) were observed between chlorophyll content and antioxidant capacity, highlighting the impact of leaf age and harvest conditions.[1,18] Phytochemical screening confirmed the presence of bioactive components such as tannins, flavonoids, saponins, alkaloids, and volatile oils, with aqueous fractions showing antioxidant capacities comparable or superior to ascorbic acid standards.[19,20] The diverse antioxidant compounds in moringa contribute to effective free radical scavenging, supporting food quality maintenance and oxidative stability during storage.

Food applications of *Moringa oleifera:* from theory to practice

The translation of *Moringa oleifera*'s chemical properties into practical food preservation has gained momentum over recent decades, with studies demonstrating efficacy across diverse food categories.

Preservation of meat and poultry

Moringa extracts have been extensively evaluated as shelf-life extenders in meat products. For example, chicken meat treated with 0.25% methanolic moringa leaf extract showed significant reductions in Aerobic Plate Count (APC) and *Escherichia coli* during 4-day refrigerated storage (4 °C) and ambient storage (25 °C).[21] Notably, this concentration maintained 0 CFU/g at the end of storage, while higher concentrations (0.5–1.0%) exhibited regrowth, suggesting an optimal dose-response relationship for antimicrobial activity.

At 1% concentration, moringa extract completely inhibited *Salmonella* growth, while total bacterial counts remained below acceptable thresholds. Similarly, treatment with 0.25–1.0% extract eliminated *Listeria monocytogenes* under low-temperature storage, showing superior anti-listeria efficacy compared to higher concentrations.

Edible coatings for fruits and vegetables

Moringa incorporation into edible coatings is a promising strategy for extending the shelf life of perishable produce.

- Avocados: CMC-based coatings containing moringa leaf extract (MLE) reduced mass loss by 50%, preserved firmness, and maintained membrane integrity, as confirmed by SEM imaging. Coatings also suppressed polyphenol oxidase (PPO) activity, delaying enzymatic browning, while retaining flavonoid content.[22,23]
- Tomatoes: Bioactive coatings combining tomato peel fiber and MLE extended shelf life to 21–28 days under ambient conditions, reducing firmness loss from 0.7 to 0.4 N/day. Sensory evaluation indicated 76% overall acceptability for coated tomatoes versus 68% for controls. A combined neem + moringa leaf extract coating (10% + 10%) further improved shelf life and fruit quality across different storage durations.[24]

Overall, sensory studies consistently show that moringa-based coatings maintain consumer acceptability while enhancing technical preservation.

Oil stabilization and oxidative protection

Moringa seed oil exhibits high resistance to auto-oxidation and serves as a natural antioxidant when blended with other edible oils. Addition of moringa oil to sunflower, canola, and soybean oils significantly reduced primary and secondary oxidation products,

enhancing shelf life.[1,3] This effect is attributed to moringa oil's high oleic acid content (68–76%) and its inherent antioxidant compounds.

Regulatory status and barriers for *Moringa oleifera*

Regulatory approval of *Moringa oleifera* as a food additive varies across regions, presenting both challenges and potential opportunities for commercialization. In the European Union, authorization under the Regulation (EU) 2015/2283 (Novel Foods) requires a dossier including toxicological assessment, compositional analysis, and comprehensive safety evaluation.[25,26] Key barriers for extract-based applications include the lack of standardized extraction methods, variability in phytochemical profiles due to origin or processing, insufficient toxicological data, and potential contaminants - such as pesticide or sterilization residues - that require documentation. Indeed, a 2019 safety evaluation by European Food Safety Authority (EFSA) for a different species, *M. stenopetala*, resulted in safety objections because of inadequate information, illustrating the high evidentiary bar for botanical products under Novel Foods.

In the United States, moringa leaf powders and other moringa-derived products currently occupy a regulatory gray area; to date no publicly available extract has obtained a formal GRAS (Generally Recognized As Safe) determination by U.S. Food and Drug Administration (FDA). GRAS status requires either documented history of safe food use before 1958 or robust scientific safety data confirming safety at intended use levels.[27] Given the limited history of moringa extracts in conventional U.S. foods and the absence of a comprehensive safety dossier, any food-additive application would likely necessitate a GRAS notice or food-additive petition.

Extending use toward a hypothetical FERA (Food Emulsifier, Regulator, Additive) recognition would impose additional requirements: validated extraction processes that yield reproducible phytochemical profiles, stability data under food processing and during storage, supply-chain GMP compliance, contaminant and residue analyses, defined composition and specification limits, and formal toxicological evaluation including Acceptable Daily Intake (ADI) and genotoxicity assessments. While preliminary safety reviews and animal studies suggest low toxicity for leaf powders and aqueous extracts,[28] public regulatory data are insufficient for additive approval, and compliance gaps remain in quality control, standardization, and long-term toxicology.

Thus, despite promising efficacy and growing consumer demand for natural preservatives, global regulatory acceptance of *M. oleifera* as a food additive depends crucially on the generation of robust safety and quality datasets, and transparent regulatory submissions.

Challenges and future perspectives

Despite promising research findings, several challenges must be addressed for widespread commercial adoption of moringa as a food preservative.

Sensory acceptance and organoleptic issues

The characteristic green colour and bitter taste of Moringa due to the presence of isothiocyanates can negatively impact sensory acceptance in certain food applications. While many studies report acceptable or improved sensory scores at low concentrations (0.5-1%), higher concentrations required for maximum preservation efficacy may cause consumer rejection. To address these issues techniques like microencapsulation of moringa extracts to mask the bitter flavour, combination with complementary flavours, and targeted applications in foods where herbal notes are acceptable or desirable.

Bioavailability and matrix interactions

The bioavailability and matrix Interactions of phenolic and fatty acid components of moringa extracts play an important role as there is different reactions involved such as protein-rich foods may bind phenolic compounds which in turn reduces antioxidant activity, while lipid components can enhance or inhibit antimicrobial action depending on the fatty acid composition. Systematic research evaluating moringa performance across diverse food systems (varying pH, water activity, ingredient complexity) is needed to optimize formulations.

Standardization and quality variation

The geographical origin, cultivation practices, harvest timing, drying methods, and storage conditions are mainly responsible factors for the variation shown in phytochemistry of Moringa. This natural variation complicates standardization efforts essential for regulatory approval and commercial consistency. Development of methods such as chemometric fingerprinting methods and establishment of quality specifications for moringa preservative extracts will be critical for further applications.

Integration with modern food processing

For Industrial use of Moringa, food processing conditions like high-temperature short-time pasteurization, high-pressure processing, modified atmosphere packaging, and extended distribution chains should be well monitored. Recent research highlights significant synergistic antimicrobial activity when moringa essential oil is combined with cinnamon and black seed oils, reducing the minimum inhibitory concentrations and showing superior efficacy compared to individual oils, with maintained biocompatibility.[29] Understanding the synergistic or antagonistic interactions with other food additives commonly used in commercial formulations will facilitate its practical implementation.

Conclusion

M. oleifera represents a scientifically proved multifunctional natural food preservative possesing both antimicrobial and antioxidant properties derived from its unique phytochemical composition dominated by glucosinolates, flavonoids, and phenolic acids. Multi-target bacterial inhibition through cell wall disruption, oxidative stress induction, quorum sensing inhibition coupled with potent antioxidant activity—create a regressive protection system suitable for a wider range of food applications. The activity showed in meat products, edible coatings, dairy stabilization, and oil preservation establishes moringa's technical viability.

However, regulatory gaps through comprehensive safety studies, standardization of extraction and quality control protocols should be addressed for full utilization of moringa's potential as a FERA-recognized food additive The future directions of research should lie in long-term safety validation, optimization of synergistic combinations with other natural antimicrobials, development of microencapsulation strategies for sensory improvement, and comprehensive assessment of moringa performance across the full spectrum of food processing conditions.

Acknowledgments

The authors sincerely express their gratitude to their respective institutions for the continuous support throughout this research. The author Sunita Singh also gratefully acknowledges the financial support received under the Research and Development Scheme, Uttar Pradesh Higher Education Directorate, Prayagraj which was instrumental in the successful completion of this work.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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